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A comparison of volume scattering strength data with model calculations based on quasisynoptically collected fishery data

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INTRODUCTION

During August 1988, the Critical Sea Test (CST) Program of the Naval Space and Warfare Command (SPAWAR) conducted its first experiment (CST I) in the Norwegian Sea. In April 1989, a second experiment (CST II) was conducted in the Northeast Atlantic Ocean, west of Great Britain and south of Iceland. As part of these experiments, the Naval Research Laboratory (NRL) as shown conducted volume reverberation measurements in the frequency range of 800 to 5000 Hz.^{1,2}

At frequencies below 5000 Hz, volume reverberation is usually caused by scattering from the swimbladders of relatively large fish. Since volume reverberation measurements can only be made in a limited number of locations and seasons, a means to use fishery data, either alone or in combination with limited acoustic measurements, to predict volume reverberation levels would be very useful.

In 1987, NRL initiated an investigation of low-frequency volume scatterers in the Norwegian Sea.³ Discussions with European fishery researchers coupled with examination of a number of their reports indicated that three species of swimbladder-bearing fish were abundant over deep waters of the region. These are Atlantic herring (*Clupea harengus*), blue whiting (*Micromesistius poutasou*), and capelin (*Mallotus villosus*). Of the three, only blue whiting were expected to be found near the CST I experimental area in the summer. Coincidentally, the blue whiting that feed in the Norwegian Sea in the summer migrate to west of Great Britain to spawn in the spring. Hence, blue whiting were also expected to be in the CST II experimental area.

Fortuitously, several European fishery laboratories conducted acoustic and trawl surveys to assess blue whiting populations in the Norwegian Sea and west of Great Britain at almost the same time as the CST experiments in

those areas. These types of surveys obtain the highest-quality data on fish distribution and abundance that are presently available for open ocean species. Hence, they provided us with an excellent opportunity to determine the extent to which fishery data could be used to predict volume reverberation through the use of a swimbladder acoustic scattering model. Comparisons of swimbladder scattering model results to volume scattering data have been successful when biological samples and acoustic data were obtained together as part of the same experiment, leading us to expect that comparisons using quasisynoptically collected fishery data could be equally successful.^{4,5}

In this paper, we will first summarize CST I and II acoustic data, which have been presented in Refs. 1 and 2. Then, the fishery data will be presented in some detail, since they are not generally available. The swimbladder scattering model will be reviewed and calculations using both raw and modified fishery data in the swimbladder model will be compared to CST results. Finally, the implications of these comparisons will be discussed.

I. CST I AND II ACOUSTIC DATA

The objective of NRL's volume reverberation measurements on CST I and II was to obtain profiles of volume scattering strength (S_v) versus depth over wide frequency and depth ranges.^{1,2} Acoustic sources for the measurements were 0.5-lb blocks of TNT detonated about 0.5 m below the surface. The primary receiver was a downward-looking Naval Research Laboratory Underwater Sound Reference Detachment (NRL USRD) model F55 line hydrophone within a reflective cone that was deployed 5–10 m below the surface. Generally, six to eight shots, fired at about 5-min intervals, constituted a data collection sequence.



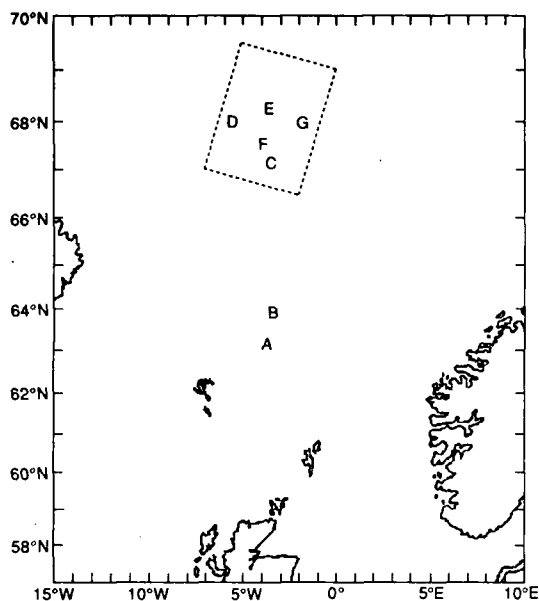


FIG. 1. CST I measurement locations. Dotted lines show the CST I test area. One night sequence was conducted at site A, one day at site B, one night and one day at site C, one night at site D, four night and three day at site E, one night and one day at site F, and three night and three day at site G.

Received signals from each TNT shot were amplified, filtered, digitized at a 20-kHz sampling rate, and stored. The stored signals were subsequently digitally filtered into $\frac{1}{3}$ -oct bands and amplitude versus time envelopes were calculated for each band. In almost all cases, there was very little variation between shots in a sequence, so average envelopes were used in the calculation of S_v versus depth profiles. S_v profiles were visually examined to determine scatterer depths. Integration over the depth ranges of the scatterers produced a series of layer scattering strength (S_L) versus frequency curves. Integration over all scatterer depths produced a total layer strength (S_T). Given the nature of the fishery data, layer depths and S_L and S_T values, rather than S_v profiles, are used in the comparisons that follow.

A. CST I

On CST I, NRL conducted volume reverberation measurements between 15 and 27 August 1988 aboard a British vessel, M/V SEA SEARCHER.¹ Twenty measurement sequences were conducted, 11 at night and 9 during the day. Of these, 18 were conducted in the CST I test area and 2 were conducted while transiting to the area. Measurement sites are shown in Fig. 1. Because CST I was a multifaceted experiment, SEA SEARCHER's movements were sometimes constrained; therefore, multiple day and night sequences were conducted at sites E and G, while only a single night sequence was conducted at site D.

Figure 2 gives layer depths and S_L and S_T versus frequency curves for site C, which are representative of all sites. All sites had multiple layers and every S_T versus frequency curve peaked between 1 and 2 kHz.

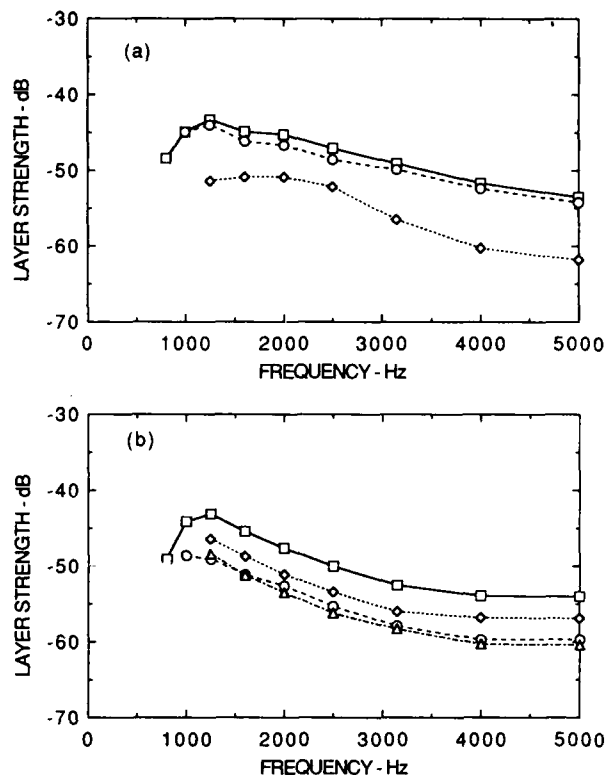


FIG. 2. Layer strengths representative of CST I. (a) Site C, day: dashed line— S_L of lower layer, 200–500 m; dotted line— S_L of upper layer, 100–200 m; solid line— S_T , 100–500 m. (b) Site C, night: dashed line— S_L of lower layer, 330–500 m; dotted line— S_L of middle layer, 85–330 m; dash-dot line— S_L of upper layer, 55–85 m; solid line— S_T , 55–500 m.

B. CST II

On CST II, NRL conducted volume reverberation measurements between 9 and 23 April 1989 aboard RMAS SALMOOR, another British vessel.² F55 data were obtained at the eight sites shown in Fig. 3. A delay in SALMOOR's sailing caused measurements at site A1 (in the

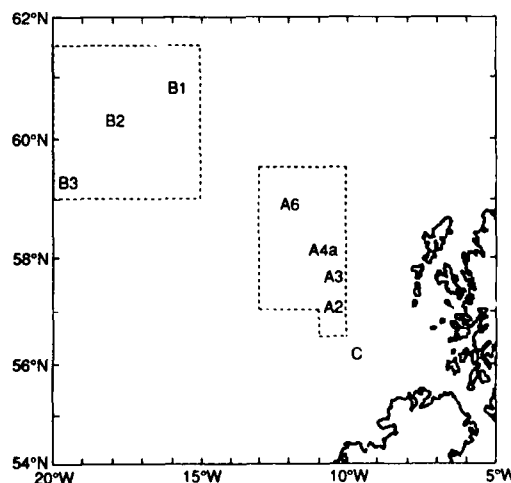


FIG. 3. CST II measurement locations. Dotted lines show the CST II test areas. One day sequence was conducted at sites A2, A4a, A6, B3, and C; one night and one day at sites A3 and B1, and two night and one day at site B2.

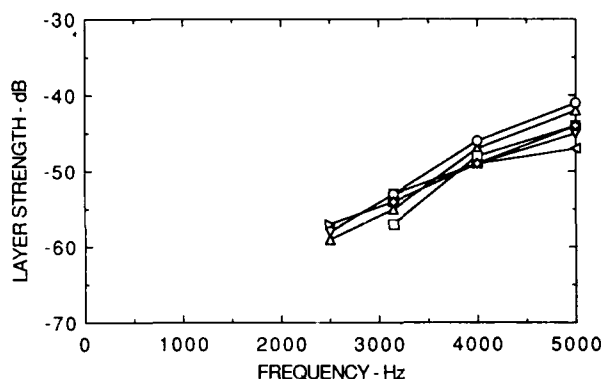


FIG. 4. Total layer strengths (S_L) for day sequences conducted in CST II test areas A and B.

southeast corner of test area A) to be canceled and those planned for sites A4 and A5 to be conducted at site A4a, an intermediate location. While returning to port, SALMOOR stopped and conducted a measurement sequence at site C, to compensate for missing site A1.

Figure 4 gives S_L versus frequency curves for the day sequences conducted in test areas A and B. During the day, scattering was observed between 200 and 800 m, with strongest scattering between 500 and 800 m at all sites. Scatterers migrated vertically at night, but S_L versus frequency curves for the night sequences are similar to those for the day. S_L curves that increase with frequency in the 2000- to 5000-Hz range are typical of those produced by scattering from small midwater fishes, such as myctophids (lantern fish). Scatterer depths are also typical for such fish. There was no evidence in these data of any scattering from larger fishes in test areas A and B.

The situation was dramatically different at site C, where layer strengths at 2500 Hz were 20 dB higher than in the test areas, as shown in Fig. 5. Scatterers were in a single layer that was 140–325 m thick between depths of 130 and 525 m. Site C was the only location on either CST I or II where significant shot to shot variations in both strength and depth of the scatterers were found as the ship drifted a mile or two during the measurement sequence. However, since fisheries data are averaged over signifi-

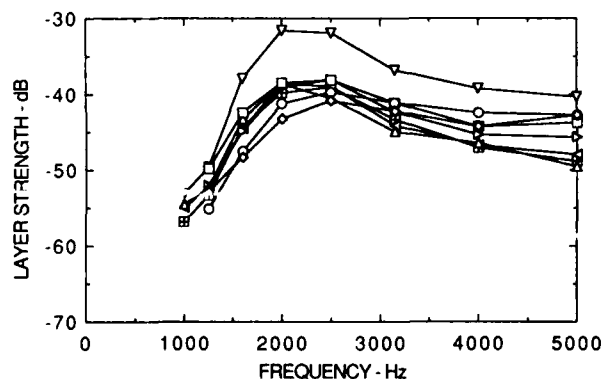


FIG. 5. Layer strengths (S_L) for the individual shots of the day sequence at CST II site C.

cantly longer distances, layer depths and S_L versus frequency curves obtained from multiple shots were averaged to produce a single depth range (160–430 m) and S_L curve for the data-to-model comparison.

II. FISHERIES DATA

During July and August 1988, blue whiting surveys were conducted in the Norwegian Sea by the Institute of Marine Research in Bergen, Norway; the Polar Research Institute of Marine Fisheries and Oceanography (PINRO) in Murmansk, USSR; the Marine Research Institute in Reykjavik, Iceland; and the Institute of Marine Fishery Research in Torshavn, Faeroe Islands. During April 1989, surveys were conducted west of Great Britain by the Bergen and Murmansk laboratories. Working documents for use by the Blue Whiting Assessment Working Group of the International Council for the Exploration of the Sea (ICES) resulted from each survey. The Working Group Chairman, Mr. Terje Monstad of the Institute of Marine Research, kindly provided these documents to us.⁶ The results of these surveys are also briefly summarized in the 1988 and 1989 reports of the Working Group.^{7,8}

The primary measurement tool on each survey was a 38-kHz echo sounder (SIMRAD EK-400) connected to an echo integrator. In addition to the acoustic measurements, numerous trawls and CTD measurements were conducted.

The primary output of the echo sounder systems is a total echo intensity (E) over some track distance, which is presented as the sum of the acoustic cross sections of all the fish encountered, in units of $\text{m}^2/(\text{nautical mile})^2$. The echo sounders also have the capability, with some limitations, to distinguish echoes from single fish and determine their individual acoustic cross sections (σ). Areal densities and total numbers of fish can then be obtained by dividing E by the mean σ . Fish length (L) distributions can also be estimated from species-specific regression equations of σ vs L . Biomass (weight) can be obtained from areal densities or total numbers of fish using species-specific weight-length relationships.

The above process assumes that all echoes are from a single species and that a statistically significant number of resolvable echoes from individuals can be obtained. Since these assumptions often do not hold, trawling is conducted to determine the species mix of the scatterers and to obtain an independent measure of length distributions for important species. Echo sounder records are then examined and fractions of E allocated to different species, based on trawl catches and knowledge of characteristics of traces produced by different species of fish, plankton, etc. It is these values of E that are generally used to determine areal densities.

Weight versus length equations are also obtained from the trawl data. These are used to calculate biomass, which is the quantity of utmost interest to fisheries, rather than numbers of individuals.

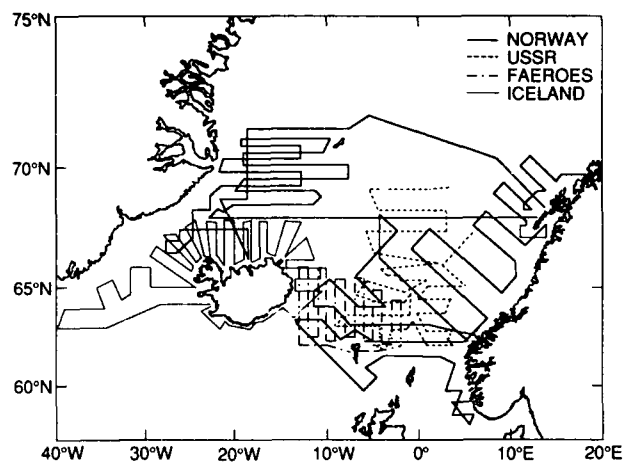


FIG. 6. Tracks of fishery vessels conducting surveys in the Norwegian Sea during August 1988.

A. August 1988

Figure 6 shows the tracks of the vessels that conducted surveys in August 1988.^{6,7} The Icelandic survey was directed toward capelin and juvenile fish around and west of Iceland; no blue whiting were encountered. Norway conducted two cruises; the one between Iceland, Greenland, and Jan Mayen focused on capelin but encountered blue whiting in the eastern part of its survey area. The other cruises focused on blue whiting. The Norwegians surveyed the area around CST I sites A and B 10 days to 2 weeks before our acoustic measurements and around sites C through G 2–3 weeks before our measurements. We have not determined the direction of the Soviet track but we estimate that they surveyed around sites A and B between 3 days and 2 weeks before and around sites C–G either between 1 and 10 days before or 3–4 weeks before our measurements. The Faroese surveyed around sites A and B about 10 days after our measurements.

Figure 7 shows the geographic distributions of blue whiting determined by the Norwegians, Faeroese, and Soviets in units of $\text{m}^2/(\text{nautical mile})^2$. The Norwegians calculated a blue whiting abundance of 2.6 million tons or 23.8×10^9 individuals. The Soviets, in their more limited

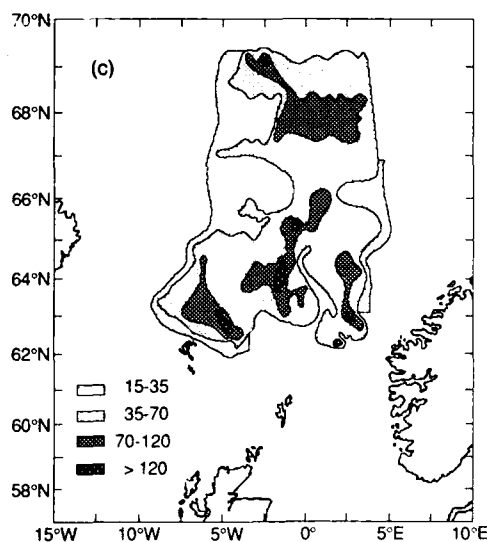
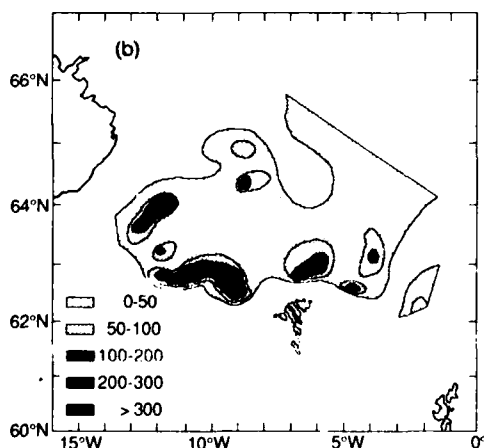
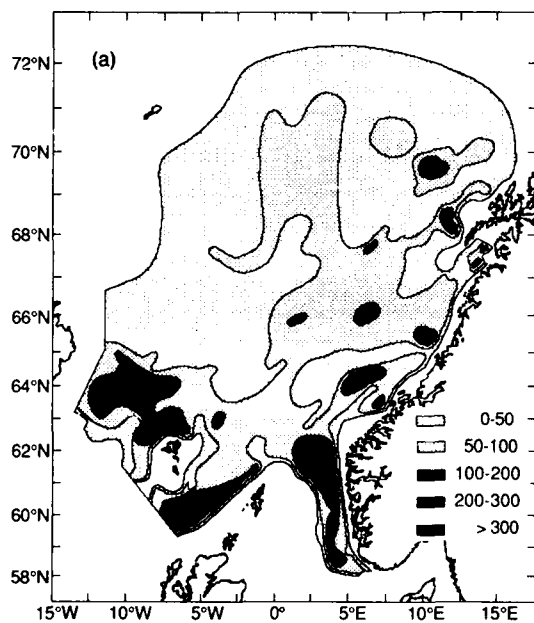


FIG. 7. Geographic distributions of blue whiting in August 1988, as measured in (a) Norwegian, (b) Faeroese, and (c) Soviet surveys. Shading shows fish density expressed as echo intensity in $\text{m}^2/(\text{nautical mile})^2$.

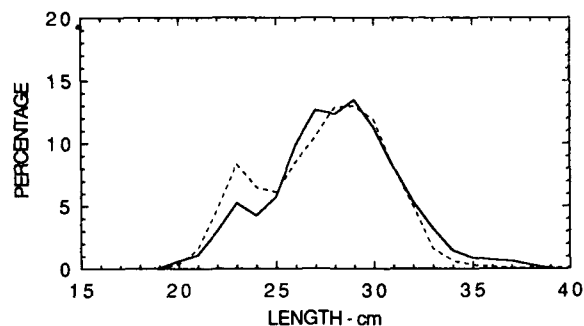


FIG. 8. Blue whiting length distributions in August 1988 at northern (solid line) and southern (dashed line) CST I sites.

survey, estimated 0.64 million tons or 4.6×10^9 individuals. The Faeroese did not calculate abundance.

The ratios of biomass in tons to numbers of individuals indicates that the Soviets saw generally larger fish than the Norwegians did. This is borne out by an examination of length distributions for the two surveys. These distributions are based on calculations from the acoustic data combined with the ground truth results of trawl catches. Each country gives a set of length distributions for rather large subareas of their respective surveys; the subareas for the surveys do not coincide. For our purposes, we have combined length distributions from appropriate subareas to produce two length distributions; a southern one that corresponds to sites A and B and a northern one for sites C-G. Figure 8 shows that there is not much difference between the two distributions. The primary difference is that there is a higher percentage of juvenile fish in the south. (Blue whiting mature when they are 22-27 cm long.)

Since biomass estimates are independent of fish depth (except as noted below), depth information is frequently not reported. Only the Norwegians mention fish depths during the August 1988 surveys, stating that blue whiting were found mostly between 200 and 400 m deep.

B. April 1989

Figure 9 shows survey vessel tracks for April 1989.^{6,8} The Soviet vessel passed through test area A while we were making volume reverberation measurements there. The Norwegian vessel passed through test area A while we were in test area B.

Figure 10 shows the geographic distribution of blue whiting in units of $\text{m}^2/(\text{nautical mile})^2$ as determined by the Norwegians. Figure 11 shows the blue whiting distribution determined by the Soviets in units of $\text{tons}/(\text{nautical mile})^2$. The Norwegians calculated a blue whiting abundance of 7.0 million tons or 67.4×10^9 individuals. The Soviets calculated 6.3 million tons or 50.9×10^9 individuals. These figures indicate that the Soviets again saw slightly larger fish than the Norwegians did, the primary difference being that the Norwegians saw a higher percentage of juvenile fish.

The Norwegians examined the size and reproductive condition of the blue whiting stock as a function of lati-

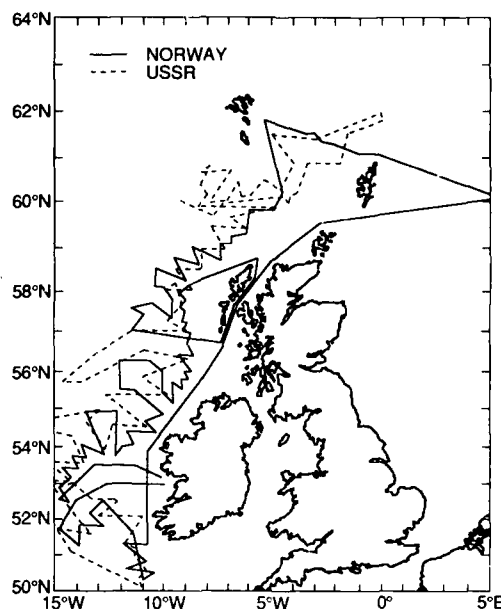


FIG. 9. Tracks of fishery vessels conducting surveys west of Great Britain during April 1989.

tude; length distributions are given in Fig. 12. Between 55°N and 59.5°N, immatures make up less than 4% of the population in each region. Progressing south, the matures become smaller and the percentage of immatures grows to 14% between 53°N and 55°N and 37% between 50°N and 53°N. The ratio of matures that had already spawned also varied with latitude. Between 50°N and 53°N, only 78% of the matures had spawned, whereas in each area between 53°N and 59.5°N, over 90% had spawned.

The difference in spawning ratio is probably more a function of time than latitude. Blue whiting migrate south

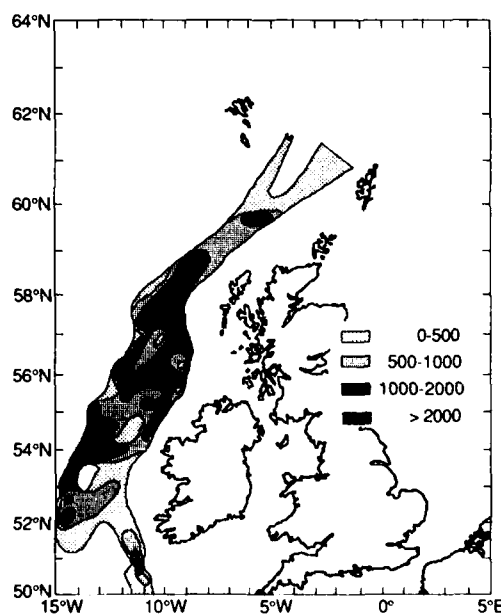


FIG. 10. Geographic distribution of blue whiting in April 1989, as measured in the Norwegian survey. Shading shows fish density expressed as echo intensity in $\text{m}^2/(\text{nautical mile})^2$.

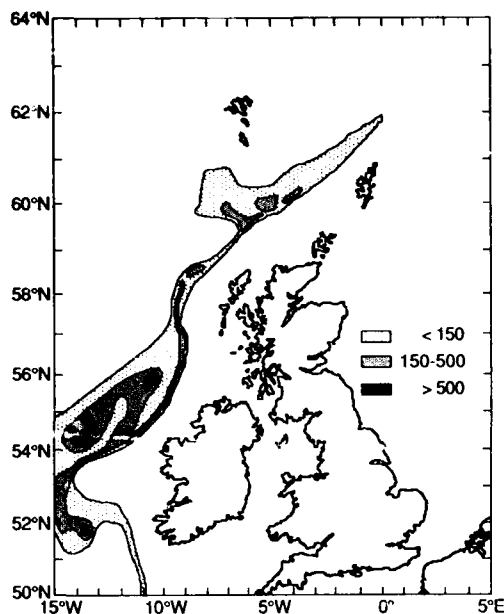


FIG. 11. Geographic distribution of blue whiting in April 1989, as measured in the Soviet survey. Shading shows fish density expressed as biomass in tons/(nautical mile)².

to spawn and after spawning migrate north again. The difference in the western edge of the Soviet and Norwegian distributions between 56°N and 60°N is almost certainly due to movement of postspawning fish that began their northward return in the 5–10 days between the two surveys. Since the surveys proceeded in a south to north direction, the southernmost region was visited earliest in the spawning season, before many of the fish had spawned.

An examination of computer printouts from the Norwegian survey indicates that about 10% of the blue whiting were between 150 and 300 m deep, 66% between 300 and 400 m, 21% between 400 and 500 m, and 3% deeper than 500 m.⁶

C. Spring/summer

The August 1988 Norwegian survey of blue whiting feeding in the Norwegian Sea saw only about 40% of the fish seen during the April 1989 surveys in the spawning area west of Great Britain. After conducting ICES-coordinated international surveys of the Norwegian Sea from August 1982 through August 1986, the Blue Whiting Assessment Working Group determined that these surveys

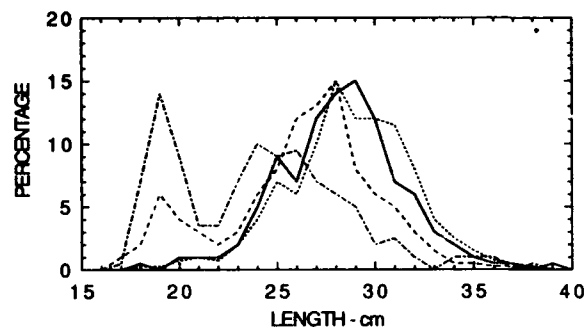


FIG. 12. Blue whiting length distributions as a function of latitude, as measured by the Norwegians in April 1989. Dotted line: 57°N–59.5°N. Solid line: 55°N–57°N. Dashed line: 53°N–55°N. Dash-dot line: 50°N–53°N.

underestimated blue whiting abundance. It was determined that the underestimates occurred because many fish were at deep depths and dispersed at such low densities over wide areas that their echoes fell below the thresholds of the echo sounders. Hence, the August 1988 surveys were conducted only to determine the geographic distribution of blue whiting and were not coordinated by ICES.⁷ Blue whiting biomass estimates are now based only on spring surveys.

III. SWIMBLADDER SCATTERING MODEL

The scattering strength of a layer of dispersed, non-acoustically interacting fish is

$$S_L = 10 \log \sum_{i=1}^n \sigma_i(f) \times 10^{-4}, \quad (1)$$

where n is the number of fish in the layer and σ is the acoustic cross section of an individual fish in centimeters squared at any given frequency (f). Blue whiting are normally dispersed in layers, so Eq. (1) is applicable.³

The model we use to calculate σ represents a swimbladder-bearing fish as a spherical shell, enclosing an air cavity, in water.⁹ The shell is a viscous, heat-conducting fluid, with the physical properties of fish flesh, and the interface between the shell and the cavity can support a surface tension. For the fish sizes and depths and acoustic frequencies of present interest, the outside diameter of the shell has no effect on the results and thermal effects and swimbladder wall tension are insignificant. The acoustic cross section of an individual fish under these conditions is given as

$$\sigma = \frac{4\pi r^2 (\rho_{0w}/\rho_{0f})^2}{[(f_0^2/f^2) - 1]^2 + [(2\pi f r \rho_{0w}/c_w \rho_{0f}) + (\xi/\pi f^2 \rho_{0f})]^2}, \quad (2)$$

where r is the radius of the swimbladder, ρ_{0w} and ρ_{0f} are the densities of water and fish flesh, respectively, c_w is the speed of sound in water, ξ is the viscosity of fish flesh, and f_0 is the resonance frequency of the swimbladder:

$$f_0^2 = (3\gamma_a P)/(4\pi^2 r^2 \rho_{0f}), \quad (3)$$

where γ_a is the ratio of specific heats of air ($\gamma_a = 1.4$) and P is the ambient pressure. These equations have essentially

the same forms as those for free bubbles in water. Reference 9 gives values of $\rho_{ow}=1.026 \text{ g/cm}^3$, $\rho_{of}=1.05 \text{ g/cm}^3$, and gives a range of possible values for ξ . Following the comments in the summary of Ref. 9, we have used $\xi=500$ P. We have also used $c_w=1.5 \times 10^5 \text{ cm/s}$.

Thus, Eqs. (1)–(3) show that to calculate S_L for a layer of fish we need to know their number, swimbladder size distribution, and depths.

One of the major functions of a swimbladder is to act as a hydrostatic organ, providing neutral buoyancy for the fish. Fish without swimbladders or fish whose swimbladders are not large enough to provide neutral buoyancy must generate lift by swimming. Some species, such as herring and capelin, have physostomous swimbladders that are open to the mouth. These swimbladders compress with depth and cannot provide neutral buoyancy at all depths. Other species, such as blue whiting, have physoclistic (closed) swimbladders and a means to pump gas into and out of the swimbladder. The daytime and nighttime swimbladder volumes of physoclists that undertake diel vertical migrations may or may not be equal: It is a question of energetics. Is it more efficient for a fish to be neutrally buoyant at both daytime and nighttime depths, be neutrally buoyant at the shallower nighttime depth and let the swimbladder compress and swim continuously at the deeper daytime depth, or use an intermediate strategy? This is an unsettled question whose answer is probably species dependent.^{10,11}

The radius of a spherical swimbladder can be written as

$$r=r(W,z), \quad (4)$$

where W is the weight of the fish and z is its depth. We will initially assume that day and night blue whiting swimbladder volumes are equal because it is the simplest strategy to model. Thus, we assume

$$r=r(W), \quad (5)$$

and will determine the validity of this assumption through the comparison of model and data.

In salt water, the condition of neutral buoyancy requires a swimbladder volume to fish weight ratio of about 0.05.¹² Measurements on blue whiting swimbladders are not available. However, measurements on other physoclists indicate that swimbladder volumes tend to be somewhat lower than the hydrostatic optimum and that there are significant variations among individuals.^{11,13–15} Based on these measurements, we developed a simple blue whiting swimbladder-size-fish-weight distribution of

$$\frac{4}{3}\pi r^3 = \alpha W, \quad (6)$$

where $\alpha=0.02$ in 10% of the fish, 0.03 in 20%, 0.04 in 30%, 0.05 in 30%, and 0.06 in 10%.

Ona¹⁵ has made measurements on both normal cod swimbladders and on cod that were about ready to spawn, whose swimbladders were compressed by their gonads. Swimbladder volumes of prespawning cod were about 60% of normal. Thus, for prespawning blue whiting the above α values would be multiplied by 0.6.

Fishery surveys usually report size distributions in terms of length rather than weight, so that a relationship between weight and length is required. Bailey¹⁶ provides blue whiting weight-length regression equations of the form

$$W=kL^3. \quad (7)$$

For adults in April after spawning, $k=0.0047$ and in February before spawning, $k=0.0062$, where W is in grams and L is in centimeters. On the basis that blue whiting feed primarily in the summer and early fall,³ we estimated that $k=0.0057$ in August. Immature blue whiting are generally slightly thinner than the adults in summer, since they grow proportionally more in length than in weight than the adults, and slightly heavier in spring, since they do not spawn. Thus, we estimated that $k=0.0052$ for immatures throughout the year.

Trawl data from the Norwegian Institute of Marine Research blue whiting surveys in the summers of 1986 and 1988 show significant variations in blue whiting length-to-weight ratios.⁶ For both August 1988 and April 1989, we have approximated these trawl data with a truncated normal distribution of

$$W=\beta kL^3, \quad (8)$$

where $\beta=0.6$ in 4% of the fish, 0.7 in 7%, 0.8 in 12%, 0.9 in 17%, 1.0 in 20%, 1.1 in 17%, 1.2 in 12%, 1.3 in 7%, and 1.4 in 4%.

Taking variations of fish and swimbladder size into account, we have, from Eqs. (6) and (8),

$$r=0.62(\alpha\beta k)^{1/3}L. \quad (9)$$

Thus, for adults in August,

$$r=0.111(\alpha\beta)^{1/3}L. \quad (10)$$

For adults in April we have several possibilities. For prespawning blue whiting with compressed swimbladders,

$$r=0.097(\alpha\beta)^{1/3}L, \quad (11)$$

while for postspawning adults whose swimbladders have returned to normal,

$$r=0.104(\alpha\beta)^{1/3}L. \quad (12)$$

There is also a possibility that blue whiting swimbladders do not return to normal immediately after spawning. If the bladders remain compressed, then

$$r=0.088(\alpha\beta)^{1/3}L. \quad (13)$$

For immatures,

$$r=0.107(\alpha\beta)^{1/3}L. \quad (14)$$

Swimbladders are not spherical but usually more closely resemble prolate spheroids. Weston¹⁷ has developed a correction factor for the resonance frequency of prolate spheroidal bubbles (f_{0e}),

$$f_{0e}=\xi f_0, \quad (15)$$

where ξ is a complicated function of major- to minor-axis ratio and its value is significant, but not large, for

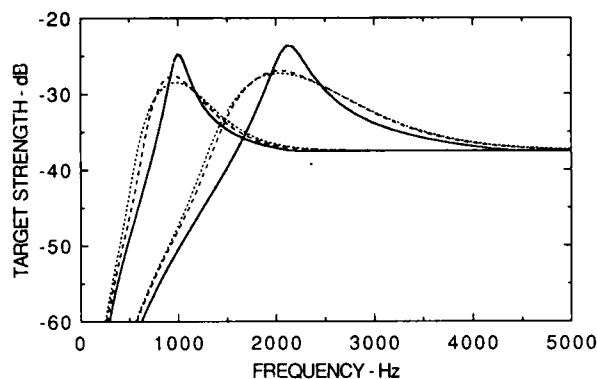


FIG. 13. Typical model results. Curves peaking near 1000 Hz are for blue whiting at or around 80 m. Those peaking near 2000 Hz are for blue whiting at or around 400 m. Solid curves are for an individual fish during August, 28 cm long, with $\alpha=0.04$ and $\beta=1$. Dashed curves include α and β distributions and the "northern" blue whiting length distribution of Fig. 8. Dotted curves include the above distributions, but the fish are in a uniform layer between 40 and 120 m or 300 and 500 m, rather than at a single depth.

swimbladders.⁹ Normal cod swimbladders have major- to minor-axis ratios of about 5, for which $\zeta=1.12$.¹⁵ It is most likely that when swimbladders are compressed by eggs or sperm, the compression is radially rather than longitudinally, so that the major- to minor-axis ratios of prespawning cod swimbladders would be about 6.5, for which $\zeta=1.16$. Since blue whiting and cod are in the same family, we have assumed the same ratios for both and, as suggested by Ref. 9, we have used the correction factor ζ in our calculations of acoustic cross sections.

At frequencies well above swimbladder resonance, in the geometric scattering region, scattering from other parts of the fish becomes significant. At these frequencies, the swimbladder model is merged with a set of frequency-independent, but aspect-dependent, empirical equations.¹⁸ For dorsal aspect, which is the aspect of interest for the downward-looking experimental configuration used on CST I and II,

$$\sigma=0.042L^2. \quad (16)$$

Given the fish sizes and depths and the maximum frequency (5000 Hz) of interest on CST I and II, Eq. (16) plays a minor role in the present data/model comparison.

Figure 13 illustrates typical model results. It shows target strengths for individual blue whiting at two different depths and how the resonance peaks become lower and broader as, first, swimbladder size distributions are included and, then, as the fish are spread throughout a layer.

IV. DATA/MODEL COMPARISON

Equations (1)–(3) indicate that the size and depth distributions of a layer of fish determine the shape of its S_L versus frequency curve, while the number of fish in the layer shifts the level. By varying r , z , and n , almost any S_L versus frequency curve can be matched; in doing so one can then deduce information about the fish in the layer. We have the opposite objective; we want to determine how closely we can correlate our knowledge of a population of

scatterers with measured S_L versus frequency curves. Our standard will be how closely the model results agree with the results of Refs. 1 and 2. In effect, this process assumes that the acoustic results are exact, which they are not. Sequence-to-sequence variations in layer strength and depth at the CST I sites where more than one day or night sequence was conducted and shot-to-shot variations at CST II site C indicate that temporal or geographic variations occur at scales that are too small for the fishery data to cope with. Therefore, comparisons are made with average day and average night curves at each site.

Swimbladder size distributions used in the modeling were determined by applying Eq. (9), with the appropriate k , to the length distribution for the appropriate area, given in Figs. 8 and 12.

Since information on fish depth for August 1988 was so poor, layer depths from the acoustic data were used to set fish depths in the modeling for CST I. The Norwegian survey data for April 1989 and acoustic layer depths at CST II site C were comparable, so, to be consistent, we again used the acoustic layer depths for CST II modeling.

Numbers of fish at a CST I site were determined by averaging the values obtained from the Norwegian, Soviet, and Faroese surveys. Only the Norwegian values were used at CST II site C. Fish were assumed to be distributed uniformly within a layer and the number of fish in a layer was expressed in terms of Φ , the number of fish in a 1-m² vertical column. Because f_0 varies with depth, the model layers were divided into ten sublayers whose thicknesses increased with depth. Calculations were done for each sublayer and the results summed to obtain S_L .

Although an S_L versus frequency curve was calculated for each layer, the most meaningful comparison is the one between measured and modeled S_L versus frequency curves. The reasons for this are related to data collection and processing techniques, modeling simplifications, and, probably, actual temporal variability of the fish. One reason is that the choice of layer depths was somewhat subjective, since the layers did not begin and end sharply and variability over the frequency band often existed.^{1,2} A related reason is that the effects of receiver sidelobes were not removed from the acoustic results. Therefore, layers appeared to extend deeper than they actually were and lower layers could be affected by upper layers, particularly at lower frequencies. At the CST I sites where multiple day or night sequences were conducted, the S_L curves had more variation among sequences than did the S_i curves. This variation appears to be real, as opposed to being caused by the choice of layer depths. Finally, in the modeling fish were distributed uniformly within a layer and size distributions were constant within a layer and in different layers. In the sea nonuniform distributions are probably the norm. All of these reasons have much more effect on individual layers than they do on all layers combined. Since we are trying to develop a general process, rather than attempting to match details, no consideration was given to refining either the data analysis or the modeling in an attempt to match each S_L curve.

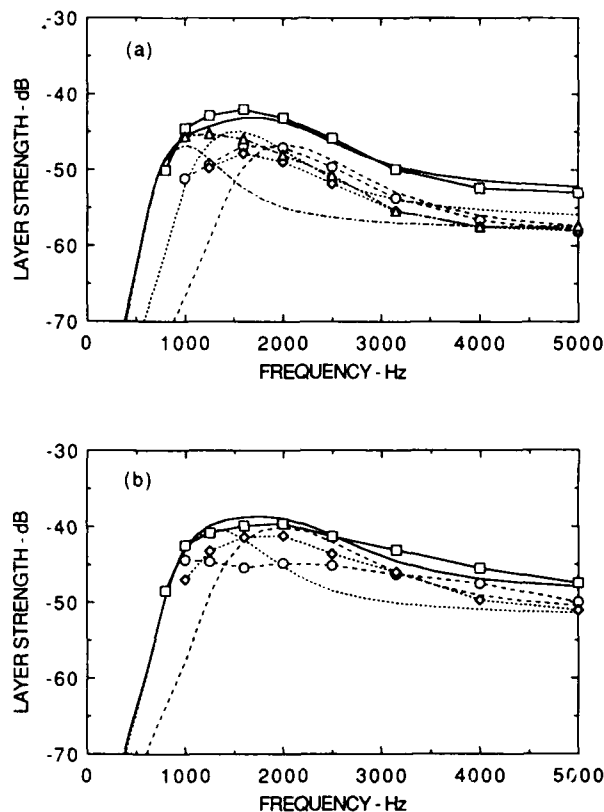


FIG. 14. Final data/model comparison for CST I site A (right) and B (day). Data curves have symbols, while model curves do not. (a) Site A: dashed line— S_L of lower layer, 300–450 m, $\Phi(\text{BW})=0.012 \text{ fish/m}^2$; dotted line— S_L of middle layer, 120–300 m, $\Phi(\text{BW})=0.020 \text{ fish/m}^2$; dash-dot line— S_L of upper layer, 45–120 m, $\Phi(\text{BW})=0.015 \text{ fish/m}^2$; solid line— S_L , 45–450 m, $\Phi(\text{BW})=0.047 \text{ fish/m}^2$. (b) Site B: dashed line— S_L of lower layer, 220–500 m, $\Phi(\text{BW})=0.060 \text{ fish/m}^2$; dotted line— S_L of upper layer, 80–220 m, $\Phi(\text{BW})=0.060 \text{ fish/m}^2$; solid line— S_L , 80–500 m, $\Phi(\text{BW})=0.120 \text{ fish/m}^2$.

A. CST I

The numbers of fish found during the August 1988 blue whiting surveys were usually not sufficient for the model results to match the CST I acoustic data; therefore, we had to increase Φ . Figure 14 shows the results obtained when Φ was increased from the survey value of $0.025/\text{m}^2$ to $0.047/\text{m}^2$ for the night sequence at site A and from $0.018/\text{m}^2$ to $0.120/\text{m}^2$ for the day sequence at site B. The agreement between acoustic data and blue whiting model results is very good at these southern sites when Φ is increased.

The situation at the northern sites in the CST I test area was quite different. Figure 2(a) shows a daytime layer between 200 and 500 m at site C peaking at 1250 Hz, while Fig. 14(b) shows that the modeled S_L curve for a blue whiting layer between 220 and 500 m peaks at 2000 Hz. Equation (3) indicates that the only ways to shift the model peak to lower frequencies are to increase the sizes of the swimbladders or decrease their depths. We cannot decrease swimbladder depths because they are fixed by the acoustic data. We cannot significantly change the relationship between blue whiting length and swimbladder radius because the fish would float to the surface. One possible

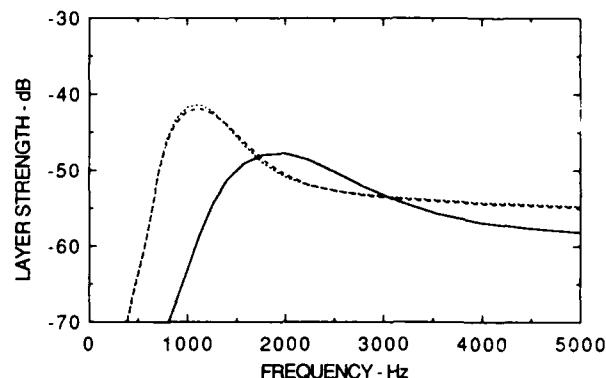


FIG. 15. Modeled layer strengths for layers between 200 and 500 m for three fish size distributions with $\Phi=0.010 \text{ fish/m}^2$. Solid line—blue whiting distribution for the northern sites (shown in Fig. 8). Dotted line—uniform size distribution of blue whiting 45–55 cm long. Dashed line—uniform size distribution of redfish 30–40 cm long.

assumption is that blue whiting in the northern area are larger than the survey results indicate. Figure 15 shows that a uniform size distribution of blue whiting between 45 and 55 cm long in a layer between 200 and 500 m deep will produce an S_L versus frequency curve that peaks between 1100 and 1250 Hz. The maximum reported size for a blue whiting is 50 cm, so the probability of a significant population of 45- to 55-cm blue whiting existing in the CST I test area is essentially zero.¹⁶

These results led to the search for another possible scatterer. An examination of the Norwegian trawl data from near the CST I test area revealed that a small number of redfish had been caught in the trawls, which were generally between 200 and 250 m deep.⁶ Redfish (*Sebastes* spp.) had been considered during the initial investigation of low-frequency scatterers in the deep waters of the Norwegian Sea, but most of the information obtained indicated that redfish were usually found near the bottom on the continental slope, so they were not examined further at that time.³ A reexamination of that information has now shown that “the pelagic existence of numerous redfish, over water much too deep for them to descend to the bottom, has been demonstrated for the Norwegian Sea” years ago.¹⁹ Redfish in the Norwegian Sea are usually found between 200 and 500 m deep.²⁰ The fishery has been primarily confined to bottom trawling on the slope, so, although the pelagic existence of redfish is recognized, their distribution and abundance in the deep waters of the Norwegian Sea has never been investigated.²¹

Redfish are slow-growing fish that mature between 10 and 15 yr of age and live for 30 or 40 yrs; adults are generally 20 to 50 cm long.^{20,22–24} They are much heavier bodied than blue whiting, which are slim. Calculations based on the Norwegian trawl catches gave $k=0.0152$ for redfish.⁶

Since redfish live at the proper depth and were caught in the CST I test area, we ran the swimbladder model for a uniform size distribution of redfish between 30 and 40 cm long between 200 and 500 m deep. The results are shown in Fig. 15. The S_L versus frequency curve for the heavy bod-

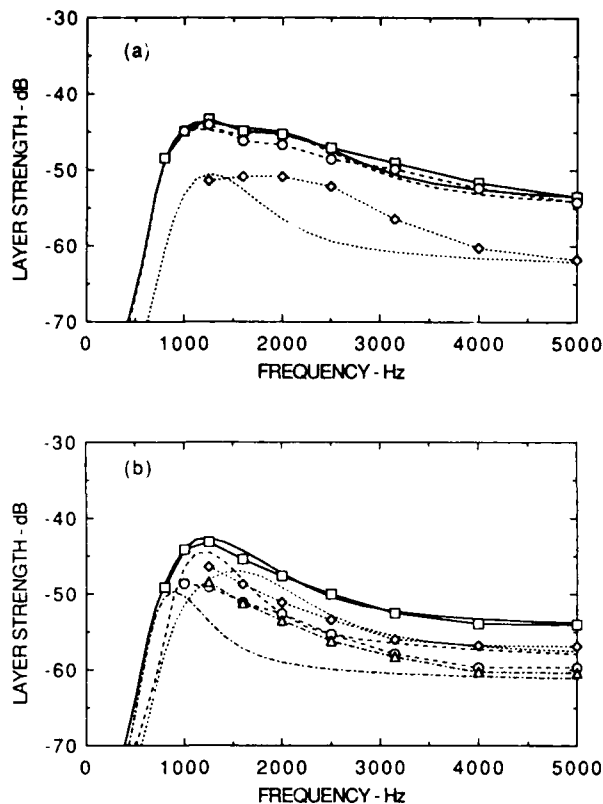


FIG. 16. Final data/model comparison for CST I site C. Data curves have symbols, while model curves do not. (a) Day: dashed line— S_L of lower layer, 200–500 m, $\Phi(\text{BW})=0.015$ fish/m², $\Phi(\text{Red})=0.005$ fish/m²; dotted line— S_L of upper layer, 100–200 m, $\Phi(\text{BW})=0.005$ fish/m²; solid line— S_L , 100–500 m, $\Phi(\text{BW})=0.020$ fish/m², $\Phi(\text{Red})=0.005$ fish/m². (b) Night: dashed line— S_L of lower layer, 330–500 m, $\Phi(\text{Red})=0.005$ fish/m²; dotted line— S_L of middle layer, 85–330 m, $\Phi(\text{BW})=0.0133$ fish/m²; dash-dot line— S_L of upper layer, 55–85 m, $\Phi(\text{BW})=0.0067$ fish/m²; solid line— S_L , 55–500 m, $\Phi(\text{BW})=0.020$ fish/m², $\Phi(\text{Red})=0.005$ fish/m².

ied 30–40-cm redfish is almost identical to the curve for the slim 45–55-cm blue whiting. Although we cannot verify that redfish are the cause of the peak at 1250 Hz at site C, none of the available information refutes this possibility. Therefore, we have assumed that redfish do indeed cause this peak and conducted our comparison of CST I sites C–G using a uniform distribution of 30–40-cm redfish. In each case we have assumed that redfish are in the deep layer both day and night and that blue whiting are alone in the upper and mid layers and may or may not be in the deep layer with redfish.

For each of the northern sites, the data/model comparison was conducted by first varying the densities of blue whiting and redfish to obtain the best match for the day and night sequences separately. Then, under the assumption that fish densities should not change from day to night (which is particularly true at sites E and G, where multiple day and night sequences were interleaved over a period of several days), day and night densities were averaged. We did not consider site D, where only a single night sequence was conducted.

Figure 16 shows the data/model comparison for single day and night sequences at site C when redfish are in-

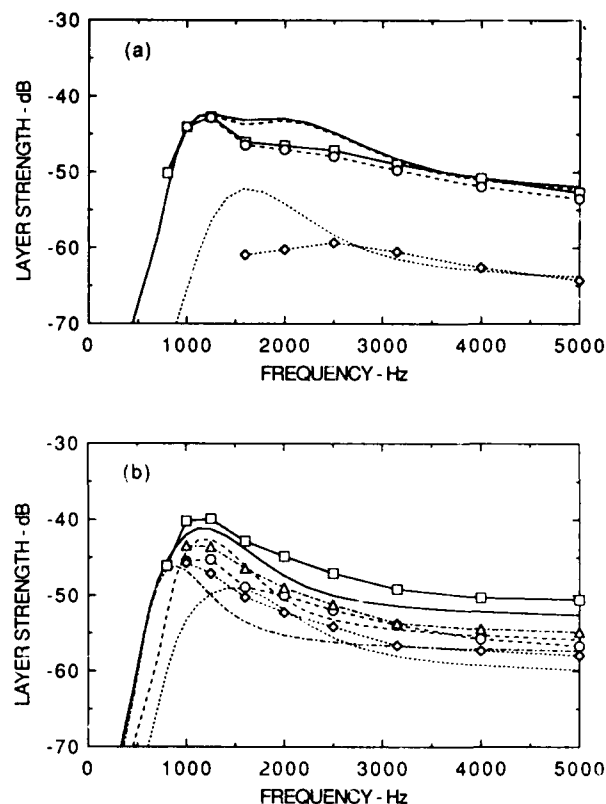


FIG. 17. Final data/model comparison for CST I site E. Data curves have symbols, while model curves do not. (a) Day: dashed line— S_L of lower layer, 300–530 m, $\Phi(\text{BW})=0.021$ fish/m², $\Phi(\text{Red})=0.008$ fish/m²; dotted line— S_L of upper layer, 210–300 m, $\Phi(\text{BW})=0.003$ fish/m²; solid line— S_L , 120–530 m, $\Phi(\text{BW})=0.024$ fish/m², $\Phi(\text{Red})=0.008$ fish/m². (b) Night: dashed line— S_L of lower layer, 300–525 m, $\Phi(\text{Red})=0.008$ fish/m²; dotted line— S_L of middle layer, 90–300 m, $\Phi(\text{BW})=0.008$ fish/m²; dash-dot line— S_L of upper layer, 45–90 m, $\Phi(\text{BW})=0.016$ fish/m²; solid line— S_L , 45–525 m, $\Phi(\text{BW})=0.024$ fish/m², $\Phi(\text{Red})=0.008$ fish/m².

cluded. Very good agreement is obtained when Φ for blue whiting is increased from the survey value of $0.011/\text{m}^2$ to $0.020/\text{m}^2$ and when, for redfish, $\Phi=0.005/\text{m}^2$.

At site E, where three day and four night sequences were conducted over a 5-d period, the best nighttime match required almost four times as many blue whiting as the best daytime match, while day and night densities of redfish were equal. Figure 17 shows the results when the blue whiting survey Φ of $0.007/\text{m}^2$ is increased to $0.024/\text{m}^2$ and $\Phi=0.008/\text{m}^2$ is used for redfish. The effects of averaging widely different day and night densities of blue whiting are apparent. Increasing blue whiting during the day causes the model S_L curve to increase above the data in the 1500–2500-Hz range. Decreasing blue whiting at night causes the model S_L curve to fall well below the data at frequencies of 2000 Hz and higher.

Figure 18 shows the data/model comparison for single day and night sequences at site F when the survey value of $\Phi=0.011/\text{m}^2$ is used for blue whiting and when $\Phi=0.012/\text{m}^2$ for redfish. At this site, the lower layer dominates both day and night data S_L curves. Although this layer did not move vertically, its strength increased by several decibels from night to day. Thus, the nighttime

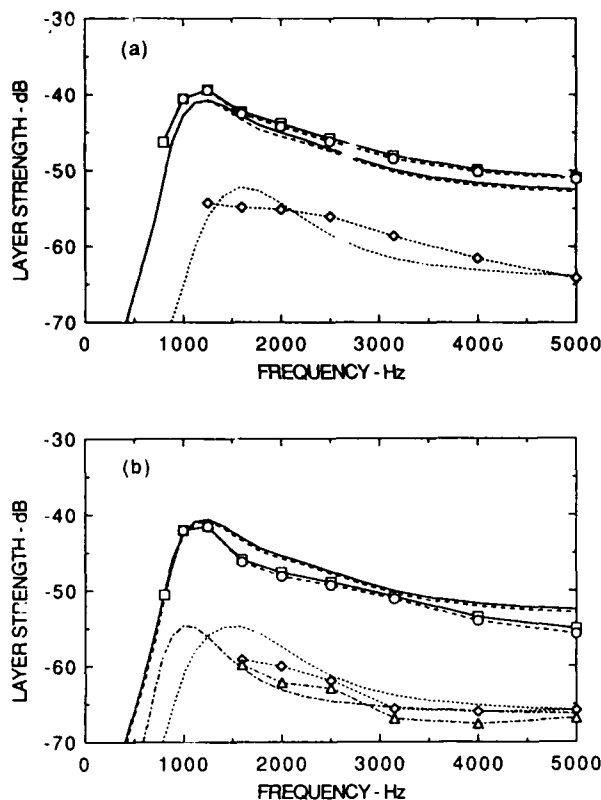


FIG. 18. Final data/model comparison for CST I site F. Data curves have symbols, while model curves do not. (a) Day: dashed line— S_L of lower layer, 300–550 m, $\Phi(\text{BW})=0.008$ fish/m², $\Phi(\text{Red})=0.012$ fish/m²; dotted line— S_L of upper layer, 200–300 m, $\Phi(\text{BW})=0.003$ fish/m²; solid line— S_T , 120–550 m, $\Phi(\text{BW})=0.011$ fish/m², $\Phi(\text{Red})=0.012$ fish/m². (b) Night: dashed line— S_L of lower layer, 300–550 m, $\Phi(\text{BW})=0.007$ fish/m², $\Phi(\text{Red})=0.012$ fish/m²; dotted line— S_L of middle layer, 120–300 m, $\Phi(\text{BW})=0.002$ fish/m²; dash-dot line— S_L of upper layer, 75–120 m, $\Phi(\text{BW})=0.002$ fish/m²; solid line— S_T , 75–550 m, $\Phi(\text{BW})=0.011$ fish/m², $\Phi(\text{Red})=0.012$ fish/m².

model S_T curve is slightly above the data and the daytime model curve is slightly below.

Figure 19 shows the results for site G, where three day and three night sequences were conducted over a period of 4 d. Increasing Φ for blue whiting from the survey value of 0.010/m² to 0.038/m² and using $\Phi=0.009$ /m² for redfish produces good agreement for both day and night.

The agreement obtained at all sites indicate that the assumption of Eq. (5), that daytime and nighttime blue whiting swimbladder volumes are equal, is valid.

B. CST II

The April 1989 geographic distributions of blue whiting determined by the Norwegians and Soviets, along with significant dates and locations along the surveys' tracks, are shown in Fig. 20. Also shown are dates and locations of the CST II volume reverberation measurements in test area A and site C. Measurements conducted in test area A from 9 to 13 April showed no evidence of scattering from anything other than small midwater fishes. Figure 20 shows that these sites were west of the western boundary of the blue whiting distribution as determined by the Soviets on 9 through 11 April, so that no scattering from large fish

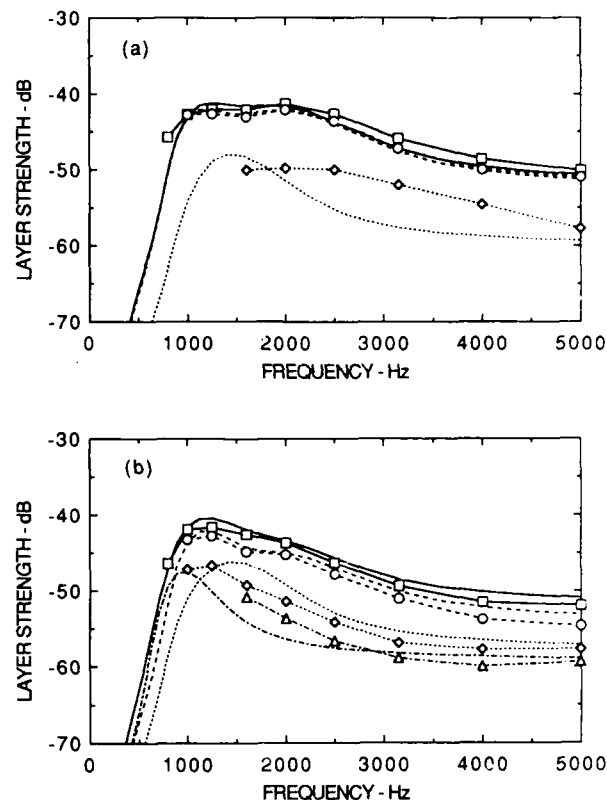


FIG. 19. Final data/model comparison for CST I site G. Data curves have symbols, while model curves do not. (a) Day: dashed line— S_L of lower layer, 270–525 m, $\Phi(\text{BW})=0.029$ fish/m², $\Phi(\text{Red})=0.009$ fish/m²; dotted line— S_L of upper layer, 125–270 m, $\Phi(\text{BW})=0.009$ fish/m²; solid line— S_T , 125–525 m, $\Phi(\text{BW})=0.038$ fish/m², $\Phi(\text{Red})=0.009$ fish/m². (b) Night: dashed line— S_L of lower layer, 290–525 m, $\Phi(\text{BW})=0.012$ fish/m², $\Phi(\text{Red})=0.009$ fish/m²; dotted line— S_L of middle layer, 100–290 m, $\Phi(\text{BW})=0.015$ fish/m²; dash-dot line— S_L of upper layer, 65–100 m, $\Phi(\text{BW})=0.011$ fish/m²; solid line— S_T , 65–525 m, $\Phi(\text{BW})=0.038$ fish/m², $\Phi(\text{Red})=0.009$ fish/m².

should have been observed. The 23 April measurements made at site C, which showed strong scattering from large fish, correlate with the blue whiting distribution deter-

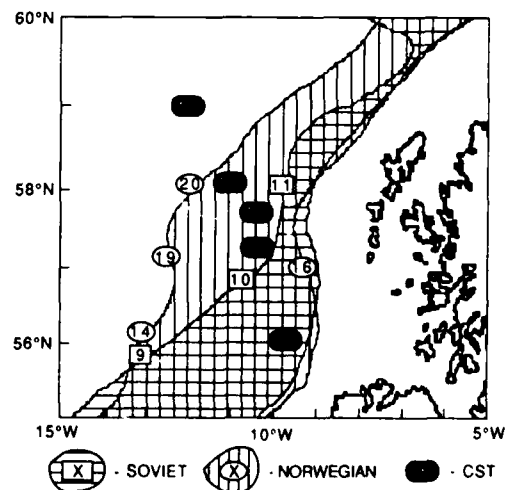


FIG. 20. Positions of the various groups on the given dates in April 1989 and corresponding limits of blue whiting distribution.

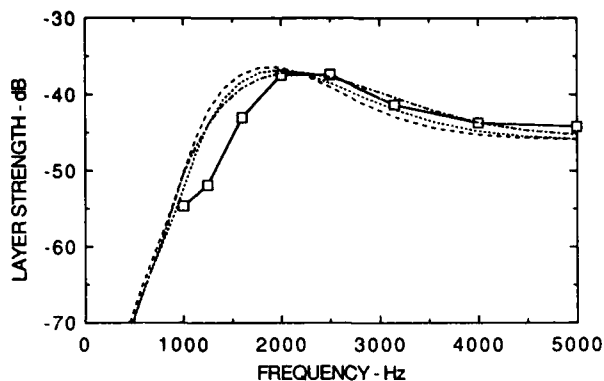


FIG. 21. Initial data/model comparisons for CST II site C for a single layer of scatterers between 160 and 430 m. All model curves are based blue whiting with normal swimbladders. Solid line— S_L data. Dashed line— S_L for blue whiting surveyed between 55°N and 57°N, $\Phi(BW) = 0.16$ fish/m². Dotted line— S_L for blue whiting surveyed between 53°N and 55°N, $\Phi(BW) = 0.18$ fish/m². Dash-dot line— S_L for blue whiting surveyed between 50°N and 53°N, $\Phi(BW) = 0.23$ fish/m².

mined by the Norwegians on 14 through 20 April, which shows that site C is well within the area where blue whiting were found. Thus, the CST II measurements geographically correlate with the fishery surveys' findings.

Site C was at 56.1°N, so for the initial data/model comparison we used the blue whiting length distribution between 55°N and 57°N and $\Phi = 0.32/\text{m}^2$ obtained on the Norwegian survey. Since almost all the adults caught by the Norwegians between 55°N and 57°N had already spawned and our measurements were about 8 d later, we assumed that all fish had spawned and that their swimbladders had returned to normal. This initial comparison produced an S_L versus frequency curve that was higher than the data, so Φ was reduced to 0.16/m². The resulting curve, shown in Fig. 21, peaks at a lower frequency than the data.

To shift the peak in the model S_L curve to higher frequency, we must assume smaller swimbladders. There are three possible scenarios that can justify smaller swimbladders. One is that the assumption that blue whiting swimbladders do not compress with depth was not valid. Another is that the fish population was smaller when the volume reverberation measurements were made than when the Norwegians conducted their survey. The third is that the fish size distributions were the same at both times but the swimbladders of the postspawners had not returned to their normal condition.

Measurements at site C were conducted during the day only, so that we cannot acoustically examine day-night depth variations in swimbladder volume. However, since CST I correlations indicate that day and night swimbladder volumes were equal in the summer, there is no reason to believe that they would not be in the spring.

The shift in the western boundary of the blue whiting distribution between 9 to 11 April and 14 to 20 April was almost certainly due to the northwestward migration of postspawning fish. Thus, it may be that when volume reverberation measurements were made at site C, the fish were not those surveyed by the Norwegians 8 days earlier

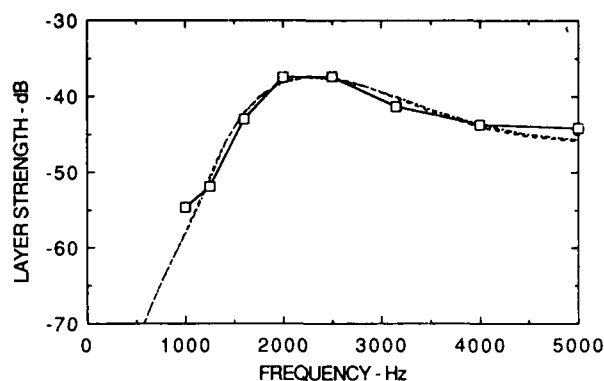


FIG. 22. Final data/model comparisons for CST II site C for a single layer of scatterers between 160 and 430 m. Solid line— S_L data. Dashed line— S_L for blue whiting surveyed between 55°N and 57°N, assuming compressed swimbladders, $\Phi(BW) = 0.20$ fish/m². Dash-dot line— S_L for blue whiting surveyed between 50°N and 53°N, assuming normal swimbladders and $L < 27$ cm, $\Phi(BW) = 0.23$ fish/m².

but were fish that had been farther south during the survey. Migrating fish may be expected to swim at a speed around 3 L/s.²⁵ The mean lengths of adult and immature blue whiting between 50°N and 53°N were about 25 and 19 cm, respectively. In 8 days, the adults could swim 280 nautical miles and the immatures 220 nautical miles or 4.7° and 3.6° latitude, respectively. Thus, in 8 days, mature fish from 51.5°N and immatures from 52.5°N could arrive at Site C.

Figure 21 also shows S_L versus frequency curves for blue whiting from between 53°N and 55°N and between 50°N and 53°N, assuming normal swimbladders and optimum densities. The model curves agree reasonably well with the data at frequencies higher than 2000 Hz, but they exceed the data between 1000 and 2000 Hz, indicating that the length distributions between 50°N and 55°N have too many large fish.

Because of different cruising speeds, size distributions of migrating fish at any location will change over time, so it is possible that the largest fish had already passed site C on 23 April and the blue whiting size distribution was smaller than those used above. Figure 22 shows the S_L versus frequency curve obtained when all fish larger than 27 cm are removed from the 50°N–53°N size distribution and an optimum density is used. This curve agrees quite well with the data.

Fish without swimbladders or fish whose swimbladders are not large enough to provide neutral buoyancy generate lift by swimming. To keep from sinking after spawning, blue whiting must either pump their swimbladders back up to their normal state or swim to generate lift. Since the annual life cycle of blue whiting is centered on the reproductive process of spawning, one would expect the energy reserves of postspawners to be very low. Thus, they would certainly stay afloat by the most energy-efficient means possible. If they begin migrating north toward the summer feeding area immediately after spawning, it is quite possible that the most efficient strategy is to migrate without immediately replenishing the gas in the swimbladder.

Figure 22 shows the results of assuming that all adults

between 55°N and 57°N had spawned by the time of the volume reverberation measurements at site C, but that their swimbladders were still in the compressed, prespawning state, so that Eq. (13) applies; again an optimum density was used. Under these conditions, the S_L versus frequency curves agree very well.

V. DISCUSSION

Good correlation between acoustic data and model results was not possible unless modifications were made to the fishery survey information upon which the modeling was based. For CST I, these modifications included increasing the density of blue whiting and including a population of redfish. For CST II, they included decreasing the density of blue whiting and assuming that the swimbladders were smaller than expected.

Modifications to the survey densities of blue whiting were expected in the case of CST I. The wide-ranging August 1988 Norwegian survey saw only 40% of the blue whiting seen in April 1989. There was no dramatic increase in blue whiting abundance between 1988 and 1989, which implies that measured blue whiting densities in August should be increased by an average factor of about 2.5 to account for unseen fish.⁸ The average increase in blue whiting densities used to obtain the best correlations for CST I was 3.0, quite close to what one would expect.

The primary difficulty with the assumption that redfish were present in the CST I test area is that, after the extensive study of the fish in the deep waters of the Norwegian Sea,³ we did not expect redfish to be found in any significant numbers over deep water. However, upon completion of the comparisons, we discussed our assumptions about redfish with Mr. Kjell Nedreass of the Institute of Marine Research in Bergen, who provided the following information.²¹ There are three species of redfish found in the Norwegian Sea. Of these, *Sebastes mentella* is more offshore and deeper than the other two species, *S. marinus* and *S. viviparus*, so that it is the most likely species in pelagic waters. It is also the proper size and at the proper depth and the proper latitude. Results of an October 1991 survey along the continental shelf and slope of Norway showed *S. mentella* between 66°N and 70°N, which corresponds to the latitude of the CST I test area. *S. mentella* caught during this survey were mostly between 25 and 45 cm long, with a mean length of 37 cm. *S. mentella* are abundant at depths of 300 to 500 m on the slope in the Norwegian Sea and sometimes move off the slope to unknown locations in deeper waters. They are also widespread during the summer at 300 to 500 m over the deep waters of the Irminger Sea, where they are plentiful enough to support a fishery. Although this information does not prove that redfish were present in significant numbers in the CST I Test Area, the circumstantial evidence leads us to conclude that *S. mentella* was probably the dominant scatterer near 1250 Hz in that area.

The correlation of the presence or absence of low-frequency scatterers in the CST II measurements with the geographic distribution of blue whiting determined by the fishery surveys strongly implies that blue whiting were re-

sponsible for the low-frequency scattering at site C. The need to decrease blue whiting density at site C is not surprising. As Fig. 20 shows, the geographic distribution off Great Britain in April changes rapidly. Thus, the density of blue whiting at any location can be expected to change rapidly also, so a decrease in density by a factor of less than 2 over 8 days is quite reasonable.

Good agreement between measured and modeled S_L versus frequency curves requires a swimbladder size distribution smaller than what would be considered normal for the size distribution of blue whiting near site C during the Norwegian survey. Agreement was obtained by postulating either that all the larger adults had left site C by the time of the volume reverberation measurements or that swimbladders of postspawning fish remained in their compressed prespawning state. We have proposed feasible explanations based on the dynamism in the condition and migration of spawning blue whiting for both possibilities but cannot prove either.

VI. CONCLUSIONS

The primary objective of this study was to determine if fishery data could be used to predict volume reverberation levels by comparing measured scattering strengths to scattering strengths obtained by using fishery data in a swimbladder scattering model. The CST I and II experiments, which were conducted in reasonably close spatial and temporal proximity to extensive blue whiting fishery surveys, provided the opportunity for the study. In the southern Norwegian Sea, measured and modeled S_r versus frequency curves agreed quite well after the densities of blue whiting were increased above those determined by the fishery surveys. In the CST I test area in the central Norwegian Sea, agreement was obtained by increasing the densities of blue whiting and including a significant population of redfish. West of Great Britain, geographic agreement between acoustic measurements and the presence or absence of blue whiting determined by the fishery surveys was excellent. Agreement between measured and modeled S_r versus frequency curves required blue whiting swimbladders to be smaller than normal for the size distribution of fish found by the survey in the area of the measurement. Reasonable arguments have been presented to justify the modifications made to the fishery data to obtain good agreement between measured and modeled results.

The correlations obtained show that volume scattering strengths in the Norwegian Sea and Northeast Atlantic can be accurately predicted from biological data if the characteristics of the scatterers are known. Modeling shows that the extent of knowledge required for accurate prediction at frequencies near and below resonance is significantly greater than at frequencies well above resonance, where scattering strengths are relatively insensitive to parameters other than fish density. Hence, scattering strengths at lower frequencies are more difficult to predict than those at higher frequencies.

The results point out a possible pitfall of relying solely on fishery data to predict low-frequency volume reverberation. Fishery research concentrates on species of present

or potential commercial value. Species of no commercial value or commercial species in areas apart from major concentrations often can be dismissed as unimportant in the fishery sense although they could be major contributors to volume reverberation at low frequencies. This appears to be the case for redfish over deep water in the Norwegian Sea.

The dynamism of the fish in the Norwegian Sea/Northeast Atlantic region makes accurate predictions of scattering strengths very difficult if high temporal and spatial resolutions are required. But contemporary fishery data, when combined with a few validating acoustic measurements, is sufficient to make seasonal predictions of average scattering strengths over relatively large areas. Since abundances and migration patterns of the fish in the Norwegian Sea have changed over the last 30 years³ and can be expected to continue to change in the future, fishery data that is more than a few years old can not be expected to provide valid predictions in this region.

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